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Application of LMS Filter for Noise Source Quantification in Environment Acoustics – A Computational Contribution

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Abstract: In the last twenty years, studies about the effects noise on hearing and the quality of life had received a great impulse, considering that noise can cause disturbances during sleep and on the health of human beings. The major parte of this studies aims to analyze the influence of industrial noise on the quality of the external environment where the people circulate or live. This type of noise is being one of the biggest causes of protest by communities at the competent agency of the cities. The methodology consists of the determination of Transfer Function (TF) between the noise source of interest and the receiving point using an adaptive filter, LMS (Least Mean Square), and a reference source (generating sine sweep). It is possible to estimate the level of noise proceeding from the source that we want to quantify based on the estimated TF and the generated signal (acoustic pressure) near the noise source. This estimation can be done at a receiving point which can be internally or externally to the industrial plant. Excellent results were obtained with numerical simulations. A numerical-computational simulation developed for control of ambient noise generates errors in the range of 5 dB. However, the filtering capacity is compromised when the reference source level of energy is reduced if compared with the energy generated by the other sources at the receiving point.

Keywords: noise source quantification, environmental noise, LMS adaptive filter, sine sweep.

NOMENCLATURE

TF = Transfer Function.
X = input signal.
Y = output signal.
f = frequency, Hz.
T = integration time, s.
$\overline{x}^2$ = exponential average.
f_{aquis} = acquisition frequency, Hz.
L = LMS filter number of weights.
$\hat{s}$ = reference source signal estimated in the receiver point.
s = reference source signal at the receiver point estimated by adaptive filter (s).
S = signal obtained close to the reference source (sine sweep).
R = noise source signal of interest at the receiver point.
SFT = Short Fourier Transform.
SPL = Sound Pressure Level, dB.
LMS = Least Mean Square.
A = signal amplitude.

Greek Symbols

μ = LMS filter convergence ratio.
α = LMS filter forgetting factor.

Subscripts

est estimated parameter.
sweep_filt sweep signal estimated by filter at the receiver point.
sweep_near sweep signal obtained near the generator.
sweep_teor sweep theoretical signal estimated at the receiver point.
i i^{th} term of the vector.
teor theoretical parameter.

INTRODUCTION

The population exposition to environmental noise, particularly in the city areas, has deserved increasing attention by the community. One of the main concerns is to study the influence of industrial noise on the external surroundings quality where people circulate or live. This type of noise is one of the major causes of protest by the communities to the city regulating organ (Handley, 1995).

With the accelerated cities growth, the invasion of industrial areas by residences is occurring with frequency. However the factories that previously were located far from the city centers are now surrounded by residences, schools, shops and hospitals. These plants, generally, are old and with noisy manufacturing processes without acoustic treatment. Since then, the main concern of the work safety engineers ware the noise affecting the worker (Aidar, 1997).

Actually inside and outside noise problems at factories have become a constant. However this study is directed to outside noise propagation.

Nowadays, it is very common to an industry receive an authority notification asking to evaluate the noise around the factory once certain cities have laws that limits the permitted noise level. This kind of acoustic problem requires a qualified professional to solve.

The principal challenge in environmental noise control is to identify which noise sources should be treated so that the noise levels at points of control satisfy the levels required by the regulations. The great problem to overcome is that a medium size industry is very complex and made up of many noise sources that contribute to the total noise level measured in the surrounding neighborhood. This is one of external noise propagation problems.

The sound pressure level (SPL) prediction in external areas adjacent to noise sources requires the analysis of noise propagation in open air. This propagation is affected by attenuation along the transmission path and is estimated considering corrections for spherical divergence, air absorption, reflections, vegetation effects, topography effect, effect of barriers and scattering in the factory. The external propagation is also affected by atmospherically conditions, such as air temperature and relative humidity (Barron, 2003).

In noise control engineering, the capacity to identify different noise sources and to determine their contribution at the control point is important. Noise source identification involves location and sound power level besides evaluation of acoustic properties such as intensity and frequency of the spectrum of the source.

In general, the characteristics of an industrial installation are:

- Many noise sources that contribute to the total SPL measured at an external receiver point (MISO – Multiple Input Single Output System);
- The noise sources cannot be switched off due to the continuous production process;
- Presence of coherent noise sources;
- The transmission path between the noise source and the external received point is complex due to reflections of the acoustic rays.

Based on these characteristics, this study has as an objective the Transfer Function estimation between the noise source to be quantified and the external receive points.

An adaptive LMS filter and a reference source which generates a sine sweep signal were used to estimate the transference function. This signal has no correlation with the noise sources present and sweeps the frequency band of interest (Muller and Massarani, 2001).

Thus with the estimated transfer function, it is possible to estimate the participation of the noise source has on the total SPL at the pre stipulated control points.

METHODOLOGY

A numerical computational simulation method was used to model the sound propagation in open air. Then the performance of this methodology was evaluated by comparing the adaptive filtering technique to obtain the transfer function between the noise source and the receiver point. All the sub-routines used for simulation were programmed in commercial software Matlab.

The simulated model is composed of noise sources propagation in open air, where only the effects of acoustic divergence (attenuation due to distance) and atmospheric absorption were considered. It is then possible to estimate the noise that reaches a receiver point due to the contribution of various noise sources by the principles of basic acoustics (Beranek and Vér, 1992).

The simulation is capable to supply:

- The transfer function (TF) between each emission point (noise source) and the receiver point given by Eq. (1), where the input is the estimated noise near the source and the output is the signal estimated at the receiver point due to the source.

$$TF(f) = Y(f) / X(f) \tag{1}$$

where *X(f)* is the input signal of the system in the frequency domain and *Y(f)* is the output signal of the system in the frequency domain (Bendat and Piersol, 1980).

- The estimated signals at 1 meter distant of each source.
- The estimated signals at the receiver point due to each source contributions.
- The total signal at the receiver point which is the contribution of all the sources.

The above signals were then compared with those estimated by the method of adaptive filtering.

To estimate the transfer function using adaptive filtering, a reference source (sine sweep signal generator) is placed close to the source being studied and the noise (at the receiver point) due to all sources presents including the sine sweep is measured. Thus using the adaptive filtering technique, the signal due to the reference source is extracted from the signal obtained at the receiver point.

The reference source signal is characterized by its frequency variation in time. Thus the use of an adaptive filter is justified since it has the capacity to accommodate the variations of the signal in time.

Finally, the Transfer Function between the two points (emitter and receiver) can be calculated using the following signals: sine sweep signal estimated close to its generator (at 1 meter of distance) and the sine sweep signal obtained at the receiver point (estimated through adaptive filtering).

The Transfer Function obtained by adaptive filtering can be used in predictive acoustics to quantify the source contribution at the receiver point. However, the source has to be located close to the reference source used to estimate the Transfer Function.

The adaptive filter uses the LMS algorithm (Least Mean Square) to obtain the best estimation. Figure 1 shows the schematic of the adaptive filtering technique used (Widrow and Stearns, 1985).

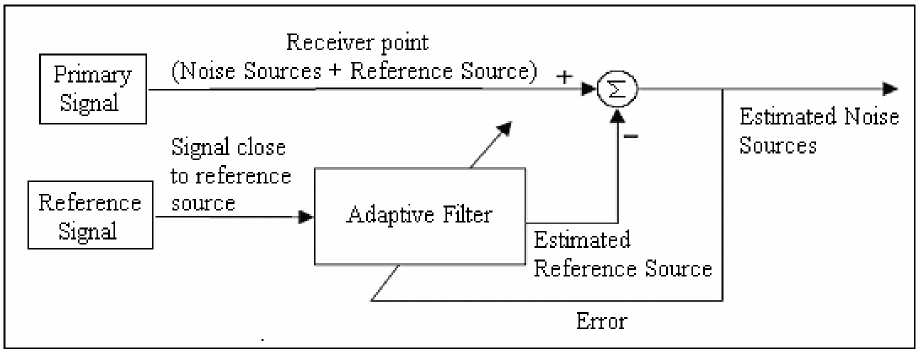

Figure 1 – Scheme of adaptive filter

The primary signal which is obtained at the receiver point (previously located) is made of contributions from all sources of the system (or study area) including the reference source. The reference source added to the system should be located close to the source being identified. The reference signal is the reference source signal at a distance of 1 meter only.

Initially a sensitivity analysis to evaluate the capability of the filter and the quality of the filtered signal was carried out. The signals amplitude that forms the reference signal and the variations of the input signal amplitude of the filter were used.

The analysis was based on Figure 1. The primary signal, obtained in the receptor point, is composed of an arbitrary source signal (constructed by the model) and a sine sweep signal. The reference signal is obtained close to the reference source and is correlated with the sine sweep which is obtained at the receiver point. The reference signal is also a sine sweep signal. The filter output signal is an estimation of the reference signal (sine sweep) and the resulting signal of the process is an estimation of the noise source level of interest.

The filter parameters were defined after a random optimization using initial values of the bands specified by the theory of LMS filters.

The estimated transfer function (*TF* between estimated sine sweep with filter - at the receiver point - and the sine sweep measured near the generator – emitter point) is expressed in Eq (2).

$$TF_{est} = 10\log_{10}(\bar{x}^2_{sweep\_filt}) - 10\log_{10}(\bar{x}^2_{sweep\_near}) \tag{2}$$

where $\bar{x}^2_{sweep\_filt}$ is the exponential average of the system input: the sweep estimated at receiver point with the adaptive filter, and $\bar{x}^2_{sweep\_near}$ is the exponential average of the system output: the estimated sweep near to the reference source. The time response for the exponential average was 125×10^{-3} seconds.

The theoretical transfer function, TF_{teor} (TF between the theoretical sine sweep at the receiver point and the sine sweep obtained near to the generator – at the emitter point) is expressed in Eq. (3).

$$TF_{teor} = 10\log_{10}(\bar{x}^2_{sweep\_teor}) - 10\log_{10}(\bar{x}^2_{sweep\_near}) \tag{3}$$

where $\bar{x}^2_{sweep\_teor}$ is the exponential average of the theoretical sweep (obtained numerically) at the receiver point. The time response for the exponential average was 125×10^{-3} seconds also.

The exponential average ($\bar{x}^2$) used in Eq. (2) and (3) can be expressed in Eq. (4).

$$\bar{x}_i^2 = \bar{x}_{i+1}^2 + (\bar{x}_i^2 + \bar{x}_{i-1}^2)/k \tag{4}$$

where $\bar{x}_i^2$ is the ith term of vector $\bar{x}^2$ and k can be expressed as in Eq. (5).

$$k = f_{aquis}T + 1 \tag{5}$$

where f_{aquis} is the acquisition frequency (Hz) and T is the integration time or response time (125×10^{-3} s). This fast integration time permits the fast events in the signal being analyzed being forgotten.

The error between the theoretical transfer function and the estimated transfer function is given by Eq. (6).

$$Error_{TF} = TF_{teor} - TF_{est} \tag{6}$$

Now it is possible to quantify the noise source of interest in the receiver point just multiplying the signal obtained close to the noise source by the obtained transfer function with de filter.

RESULTS AND DISCUSSION

The sine sweep used for sensitivity analysis simulation has the following characteristic: ten (10) seconds duration in the 50 Hz to 2000 Hz band.

The best estimated parameters values of the filter to be used with the above sweep are: number of weights, L=20; convergence ratio, $\mu=8\times10^{-2}$ (where $0< \mu<1$); and forgetting factor, $\alpha=0.01$ (where $0< \alpha<1$).

In Fig. 2 is showed the spectrogram (Short Fourier Transform - SFT) of the sweep used for sensitivity analysis, which is the sine sweep obtained in the receiver point. The spectrogram is estimated using the Matlab function *specgram*.

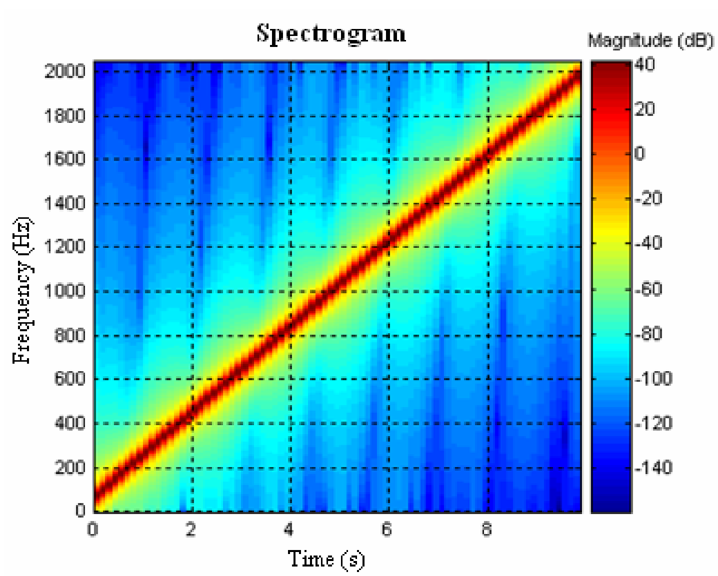

Figure 2 – Spectrogram of signal

For the sensitivity analysis, the following conditions were simulated: five configurations of the primary signal with nine configurations of the reference signal of the filter. The results are shown in Fig. 3. The vertical axes of the Fig. 3 is the error between the estimated signal of the reference source in the receiver point ($\hat{s}$) and the signal of the reference source in the receiver point estimated by adaptive filter (s). The horizontal axis is the ratio S/s, where S is the signal obtained close to the reference source (sine sweep). The results are function of the amplitude ratio s/R, where R is the noise source of interest, or the noise source to quantify, obtained in the receiver point. The configuration SR1 stands for an amplitude of *s* 40% greater than the R, or (s/R = 1.40); SR2 stands for s/R = 1.00; SR3 stands for s/R = 0.70; SR4 stands for s/R = 0.40; and SR5 stands for s/R = 0.12.

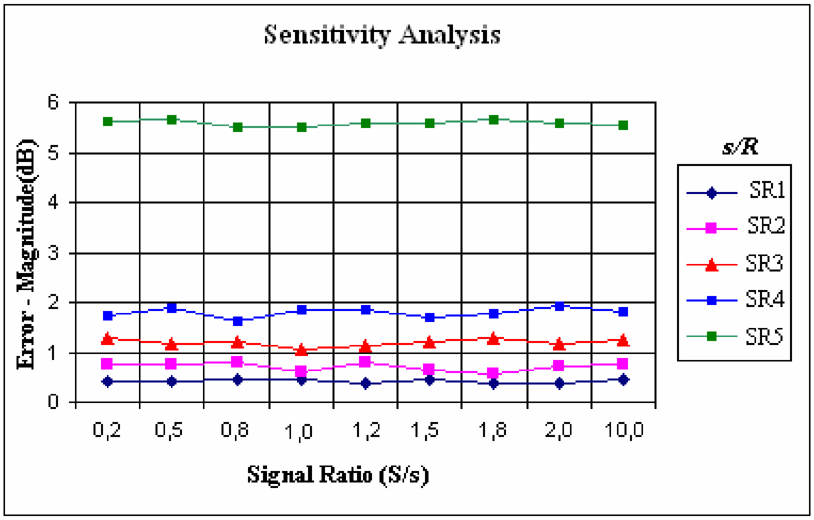

Figure 3 – Sensitivity Analysis Results

Analyzing the Fig. 3 one can see that the larger the ratio s/R the smaller the error ($\hat{s} - s$), whereas the ratio S/s does not affect significantly the error ($\hat{s} - s$).

So we can conclude that, the greater the contribution of the reference source to the sound pressure level measured at the receiver point the better is the filter results. That is, the more precise will be the transfer function estimation. Huertas and Antelis (2005) have proved these results at their work.

Figure 4 shows the schematic representation of the simulation model for open air propagation.

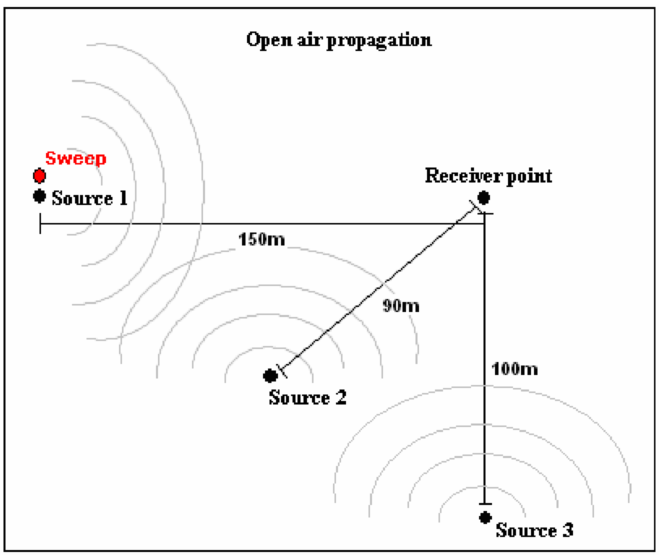

Figure 4 – Simulation model with three noise sources

The objective of this simulation is to estimate the noise from source 1 that reaches the receiver point. Hence the reference is placed near to source 1.

Table 1 lists the frequencies present in the signals of the sources used in the simulation model.

Table 1 – The simulation model noise sources frequencies.

Source	Frequencies (Hz)
1	300; 500; 700; 1000; 1300; 1700; 2000.
2	200; 400; 500; 1000; 1200; 1850.
3	125; 200; 500; 1300; 1550; 1800.

Applying the sources signals (including the reference source) that reach the receiver point to the schematic shown in Fig. 1, the sweep that reaches the receiver point without influence of the adjacent sources was obtained. Figure 5 shows the input signals of the LMS algorithm.

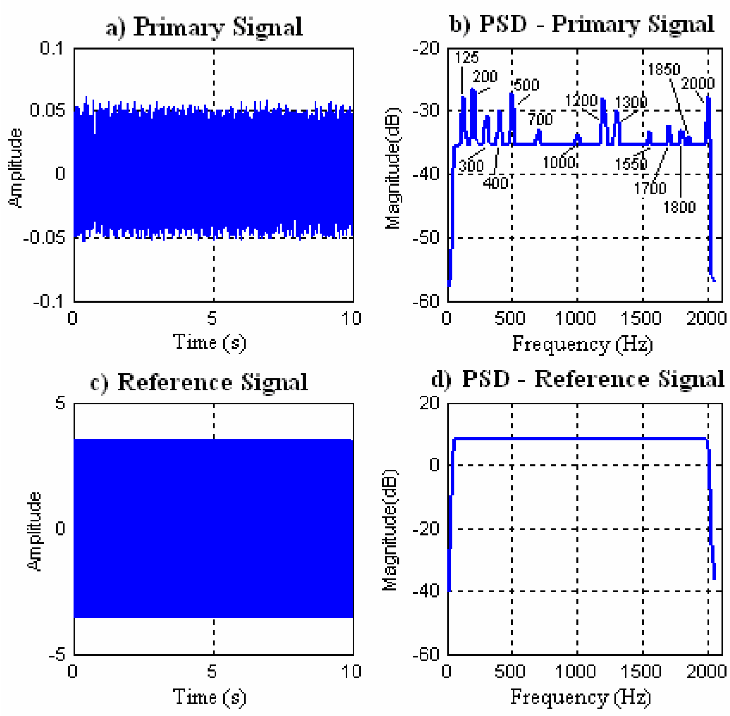

Figure 5 – Signals of the LMS algorithm.

The Fig. 5 shows: Figure 5-a the time domain primary signal; Fig. 5-b the PSD - Power Spectral Density of the primary signal; Figure 5-c the time domain reference signal and Fig. 5-d the PSD of the reference signal. The goal signal is the sweep estimation that reaches the receiver point.

As shown in Fig. 5-c, the sweep generated by the reference source placed near to source 1 gives a linear signal in the 50 Hz to 2000 Hz band in 10 seconds time interval.

After using the LMS adaptive filter, the sweep estimation that reaches the receiver point is shown in Fig. 6-a. Figure 6-b shows the error (theoretical sweep minus estimated sweep). Based on the error plot one can see a satisfactory performance of the filter for this model.

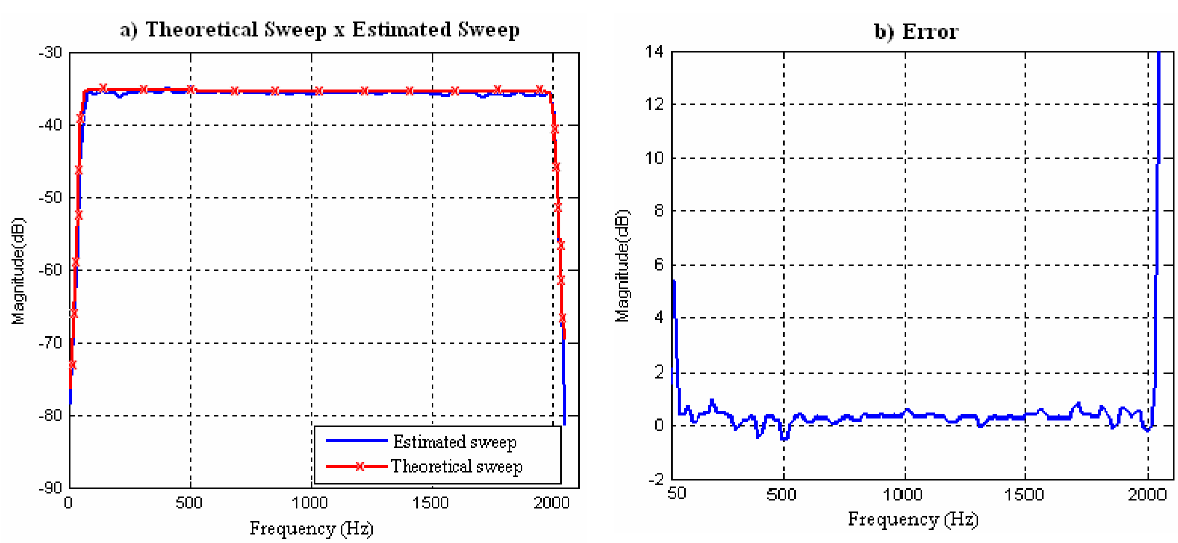

Figure 6: a) Comparison between theoretical and estimated sweep at receiver point. b) Error of theoretical sweep in relation to estimated sweep.

The large error for low frequencies (bellow 60 Hz) shown in Fig. 6-b is due to the filter convergence time. However the error is less than 1 dB from 60 Hz to 2000 Hz. This is due to the major contribution of the sweep energy generator at the receiver point as concluded based on the sensitivity analysis. The energy contributions of the noise sources at the receiver point are shown in Fig. 7.

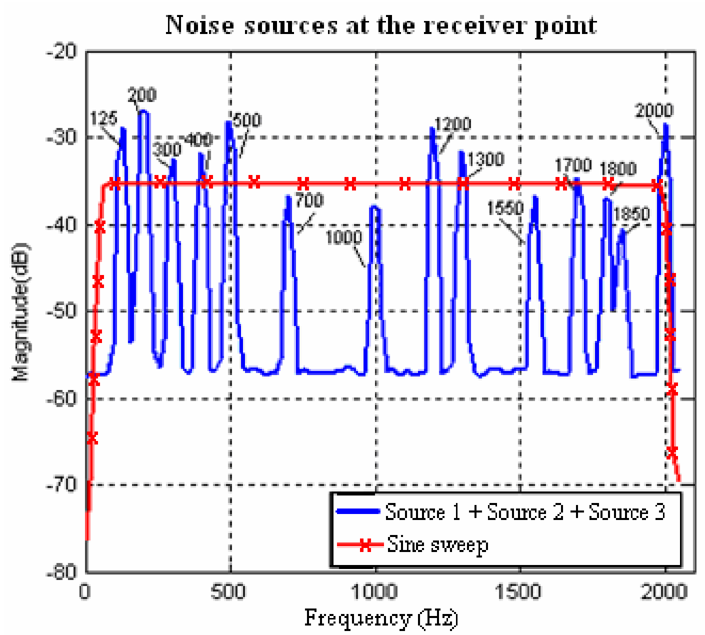

Figure 7 – Contribution of the noise sources at the receiver point.

The frequencies: 125, 200, 300, 400, 500, 1200, 1300 and 2000 Hz in the Fig.7 have much more energy than the sine seep signal in the 125-200 Hz range. This fact explains the obtained error (less than 1 dB) using the adaptive filter showed in the Fig. 6-b.

Fig. 8-a shows the estimated transfer function and the theoretical transfer function between source 1 and the receiver point. The error between theoretical transfer function and estimated transfer function is shown in Figure 8-b. The transfer functions were calculated using Eq. (2) and (3).

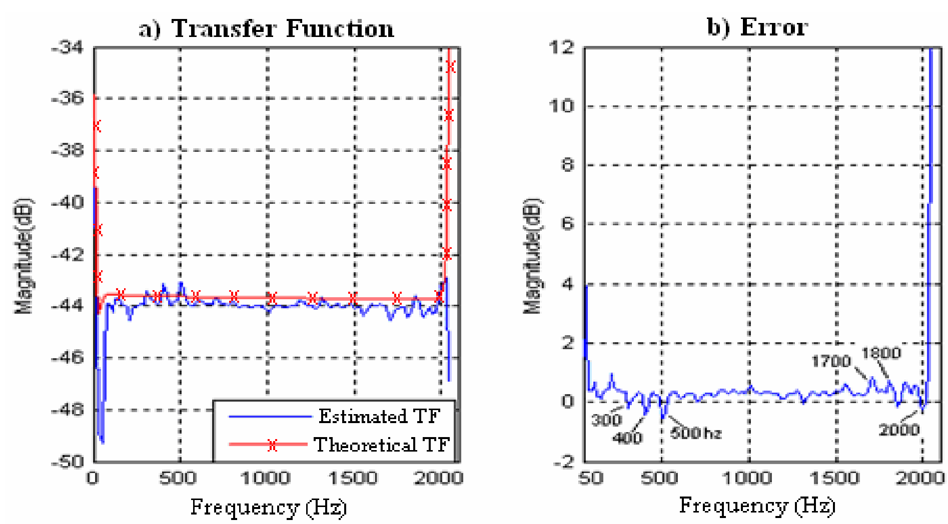

Figure 8: a-Spectral density power of the estimated transfer function and the theoretical transfer function. b- Error of the theoretical transfer function.

In the range of 60 Hz to 2000 Hz the error was less than 1 dB shown that the estimated transfer function between the emitter (source 1) and the receiver point was very good.

To clarify a little more the previous sensitivity analysis another simulation with a variable amplitude sweep was realized. The new sweep signal had attenuation in amplitude with increase in frequency as shown by the Eq. (7).

$$A = 2.6153 - 0.0013f \tag{7}$$

where A is the amplitude and f is the frequency.

The variable amplitude sweep models open air noise propagation. The filter parameters were not modified since the sweep velocity was maintained. The signals that reach the receiver point (noise sources and reference source) are shown in Fig. 9-a. Figure 9-c is the reference signal (sweep obtained close the generator). Figure 9-b and Fig. 9-d shows the power spectral density of the primary and reference signal, respectively.

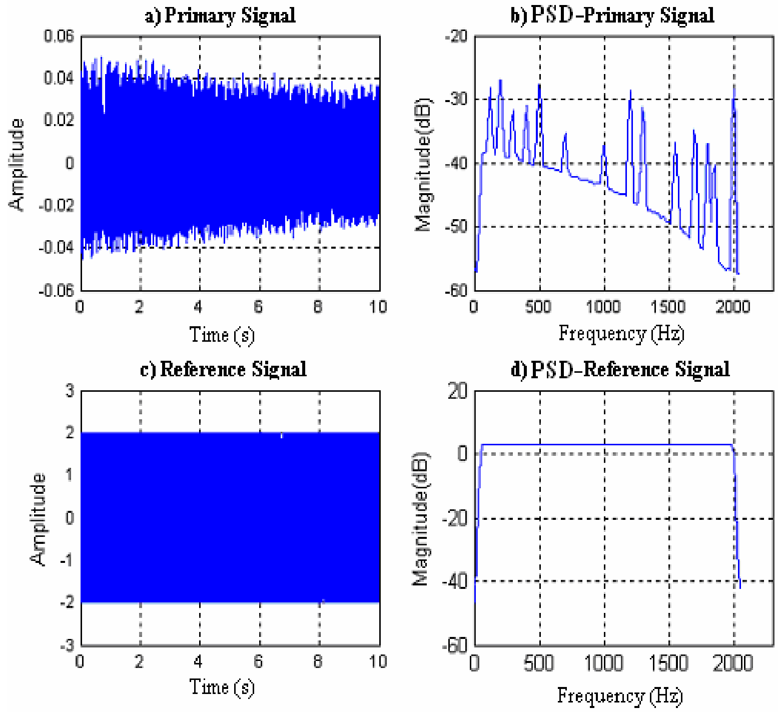

Figure 9 – Input signals of the LMS algorithm.

Figure 10-a shows both the theoretical and estimated sweep at the receiver point. Figure 10-b shows the error (theoretical sweep minus estimated sweep).

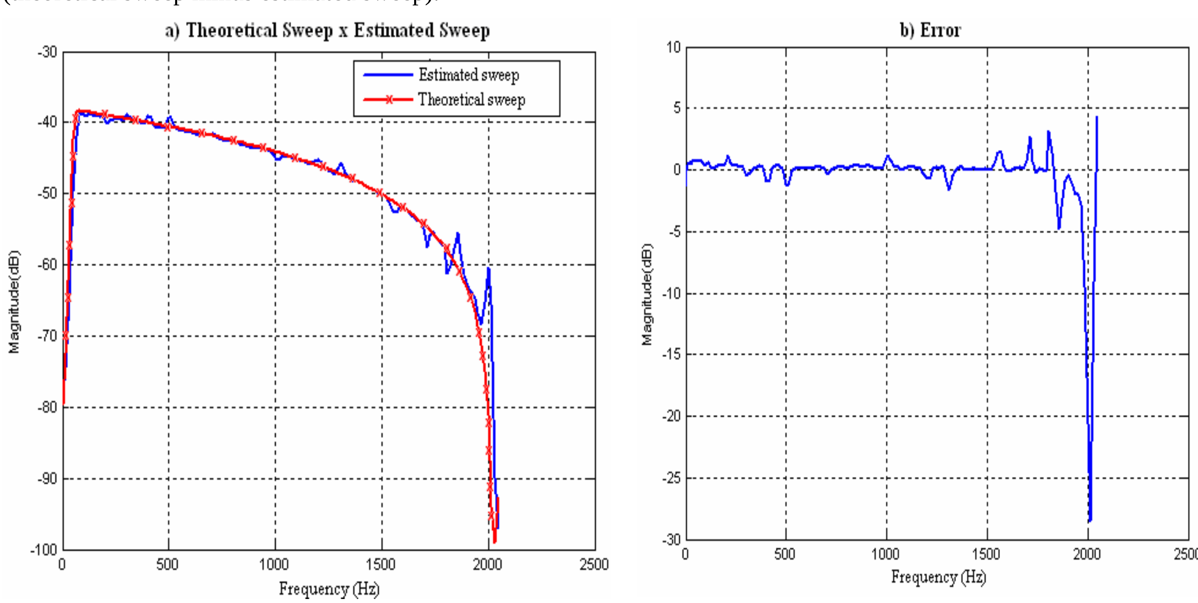

Figure 10: a) Comparison between theoretical and estimated sweep at receiver point. b) Error (theoretical sweep minus estimated sweep).

Figure 10-a showed that the filter eliminated a large part of the energy contributed by the noise sources 1, 2 e 3. However, for high frequencies (above 1750 Hz) this is not true, since at high frequencies the energy of the sine sweep signal is less than the energy sum of the three contributing sources. Figure 10-b shows that up to 1875 Hz the maximum error is 5 dB, and 28 dB maximum above 1875 Hz.

CONCLUSION

The objective of this study is to determine the transfer function of a MISO system using adaptive filtering and a reference source signal (sine sweep signal generator). The inputs are the simulated noise sources of an industry plant and the output is the noise at a control point in the local community, externally to the plant.

The main conclusions were:

1- The sensitivity analysis with the adaptive filter using various energy levels of the primary and reference signals showed that reduction of the energy level of the reference signal in the primary signal reduces the filtering capacity. This compromises the quality of the filtered signal making it unusable.

2- The above characteristic was observed in the simulation with three noise sources in open air environment.

3- For a filter good performance the reference signal has to be correlated with the noise that we want to eliminate of the primary signal only. The energy level of the reference signal is not so important.

4- The adaptive filter parameters should be optimized previously with an objective function that gives a good convergence and good filtering capacity in order to minimize the error between the theoretical and estimated signals. The adaptive filter parameters depend on the sine sweep signal velocity.

5- The obtained results using the adaptive filter had good signal-noise ratio (17 dB) considering only the reference source signal that reaches the receiver point.

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